AFRL-ML-WP-TR-1998-4199

## RETIREMENT FOR CAUSE/ENGINE STRUCTURAL INTEGRITY PROGRAM

## ADVANCED CAPABILITY MOTION CONTROLLER

PEYTON COLLINS


AMERICAN ROBOT CORPORATION
308 HIGH TECH DRIVE
OAKDALE, PA 15071
(724) 695-9000

DATE: 16 OCTOBER 1998

FINAL REPORT FOR AUGUST 1996 THROUGH APRIL 1998

MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
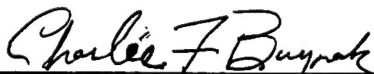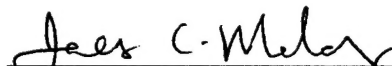WRIGHT-PATTERSON AFB, OH 45433-7817

19990524 061

# NOTICE

WHEN GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA ARE USED FOR ANY PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY GOVERNMENT-RELATED PROCUREMENT, THE UNITED STATES GOVERNMENT INCURS NO RESPONSIBILITY OR ANY OBLIGATION WHATSOEVER. THE FACT THAT THE GOVERNMENT MAY HAVE FORMULATED OR IN ANY WAY SUPPLIED THE SAID DRAWINGS, SPECIFICATIONS, OR OTHER DATA, IS NOT TO BE REGARDED BY IMPLICATION OR OTHERWISE IN ANY MANNER CONSTRUED, AS LICENSING THE HOLDER OR ANY OTHER PERSON OR CORPORATION, OR AS CONVEYING ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY IN ANY WAY BE RELATED THERETO.

THIS REPORT IS RELEASABLE TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS). AT NTIS, IT WILL BE AVAILABLE TO THE GENERAL PUBLIC, INCLUDING FOREIGN NATIONS.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

CHARLES F. BUYNAK, Project Engineer
Nondestructive Evaluations Branch
Metals, Ceramics & NDE Division

JAMES C. MALAS, Acting Chief
Nondestructive Evaluations Branch
Metals, Ceramics & NDE Division

GERALD J. PETRAK, Assistant Chief
Metals, Ceramics & NDE Division
Materials & Manufacturing Directorate

IF YOUR ADDRESS HAS CHANGED, IF YOU WISH TO BE REMOVED FROM OUR MAILING LIST, OR IF THE ADDRESSEE IS NO LONGER EMPLOYED BY YOUR ORGANIZATION, PLEASE NOTIFY, AFRL/MLLP, WRIGHT-PATTERSON AFB OH 45433-7817 AT 59819 TO HELP US MAINTAIN A CURRENT MAILING LIST.

COPIES OF THIS REPORT SHOULD NOT BE RETURNED UNLESS RETURN IS REQUIRED BY SECURITY CONSIDERATIONS, CONTRACTUAL OBLIGATIONS, OR NOTICE ON A SPECIFIC DOCUMENT.

# REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

| 1. AGENCY USE ONLY (Leave blank) | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | OCTOBER 1998 | FINAL REPORT FOR AUG 1996 - APR 1998 |

**4. TITLE AND SUBTITLE**
RETIREMENT FOR CAUSE/ENGINE STRUCTURAL INTEGRITY PROGRAM
ADVANCED CAPABILITY MOTION CONTROLLER

**5. FUNDING NUMBERS**
C    F33615-96-C-5259
PE   63112
PR   3153
TA   00
WU   23

**6. AUTHOR(S)**

PEYTON COLLINS

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
AMERICAN ROBOT CORPORATION
308 HIGH TECH DRIVE
OAKDALE, PA 15071

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
MATERIALS & MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AFB, OH 45433-7750
POC: CHARLES F. BUYNAK, AFRL/MLLP, 937-255-9807

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

AFRL-ML-WP-TR-1998-4199

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION AVAILABILITY STATEMENT**

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

**12b. DISTRIBUTION CODE**

**13. ABSTRACT (Maximum 200 words)**

The Air Force has developed, tested, and implemented an on-line-replacement upgrade for its Retirement for Cause (RFC) capability. It has replaced an expensive, custom designed, obsolete, green screen/numeric keypad controller with a commercial off the shelf, Windows NT, active matrix touch screen PC with better motion controlled performance and approximately half the cost. Four systems have been installed to date and are operational.

**14. SUBJECT TERMS**
Retirement for Cause, Engine Structural Integrity, Eddy Current Inspection Station Nondestructive Evaluation.

**15. NUMBER OF PAGES**
30

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | SAR |

## Table of Contents

## List of Figures

**List of Tables**

# Foreword

This final report covers all work performed under contract #F33615-96-C-5259 by American Robot Corporation from 23 August 1996 to 23 April 1998.

This contract was initiated under Project 3153, "Nondestructive Inspection/Evaluation", Task 315300. The work was monitored by Charles F. Buynak, Metals, Ceramics & NDE Division, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio.

Peyton Collins served as Principal Investigator for American Robot Corporation.

# 1.0 Introduction

In the early 1980's the Air Force introduced a machine to perform Non-Destructive Evaluation (NDE) for automated inspection of rotating components of gas turbine engines. This machine was developed under the Air Force Retirement For Cause (RFC) portion of its Engine Structural Integrity Program (ENSIP). The machine utilizes Eddy Current technology to find small flaws or cracks, in the components under test. With this inspection technique, a specially designed probe is placed in contact with the surface of the component, and an eddy current is induced in the material with a tiny transmitter coil in the probe tip. An adjacent pickup coil receives the reflected energy, and a digital signal processing computer analyzes the feedback to determine if there is a flaw in the material at the point of contact of the probe tip. In order to inspect a component, the probe tip must be moved over the complete surface of the component where flaws might be expected.

The machine that was developed is known as an Eddy Current Inspection Station, or ECIS. The ECIS automates the inspection process by prompting the operator to load the part, requesting serial number and cycle data, picking up the appropriate probe from a carousel of available probes, and manipulating the probe over the component's surface while analyzing the data returned from the probe. If a flaw is found and verified, the component is discarded or "retired for cause." If no flaws are found, the component is returned to service.

The ECIS consists of a turntable upon which the component is placed, a probe carousel, and a six-axis cantilever style gantry robot. Many different inspection techniques have been developed over the years for different component geometries, but the most common inspection requires that the component be rotated on the turntable while the gantry robot slowly moves the probe across the part. The combined motion of the robot and the turntable assure that the proper surface coverage has been attained to detect any flaws in the component.

The ECIS control system consists of three interlocked computers. The "eddy current instrument" is a computer which controls the low level function of the excitation/response of the probe. The "robot controller" is a computer which controls the motion of the robot and machine I/O functions (solenoids, limit switches, etc.). The "station computer" is the supervisory computer which interfaces to the operator, collects and analyzes the data coming from the eddy current instrument, and issues high level motion and I/O commands to the robot controller. The station computer also communicates to a facility wide host computer which maintains a database of the various components and their test results.

## 1.1 Project Scope

The Air Force intends to continue use of the ECIS machines for many years to come. In order to enhance the functionality of the ECIS, and to eliminate obsolete components which are difficult and expensive to replace, the Air Force has undertaken a project to upgrade several areas of the ECIS system. One of the areas requiring improvement was identified as the robot controller. American Robot Corporation (ARC) was selected as the contractor tasked with replacing the obsolete robot controller with an upgraded version. This portion of the overall ECIS upgrade has now been completed, and this is the final report summarizing the results of this effort.

Instead of developing a robot controller from the ground up specifically for the ECIS system, ARC has used its ARMotion robot controller, a Commercial Off The Shelf (COTS) component to replace the obsolete robot controller in the ECIS system. This was a relatively small effort compared with the development of a new system, and has many advantages over a custom design. The effort was broken down into several subtasks:

- Structural dynamic analysis of the ECIS manipulator

- Development of a kinematic model for the ECIS manipulator

- Development of a set of interface cables to adapt the ARMotion controller's standard connectors to the motor, encoder, and I/O connectors of the ECIS system

- Development of a special feature (Threshold Interrupt) required by the ECIS machine and not previously implemented in the standard ARMotion system

- Development of an application program that emulates the obsolete robot controller, so no modifications have to be made to the other system components, and the upgraded controller can be a "drop-in" replacement part

- Installation of the upgraded robot controller at an ALC facility

- Testing and qualification of the system in the production process

The scope of this research project was to deliver only one controller, but both SA-ALC and OC-ALC have already implemented three additional controllers externally to this project. To date, four controllers have been delivered.

## 1.2 Background

ARC is a Pittsburgh, PA based robotics company. It manufactures several product lines which are sold to the automotive, aerospace, and general industrial markets. These include articulated robots, gantry robots, and robotic motion controllers. ARC's "ARMotion" universal robot controller has been in continuous development since its inception in the early 1980's, and now one of ARC's primary businesses is applying the ARMotion controller to manipulators manufactured by other vendors. While a portion of ARC's ARMotion sales are for new systems, the primary market is retrofitting existing machinery.

Many manufacturing facilities have process machinery such as robots and specialized manipulators like the ECIS system. These machines are becoming obsolete as the fast pace of Computer Integrated Manufacturing marches on. Replacement components such as circuit boards, 5 ¼" disk drives, 10Mbyte hard disks, etc., become impossible to source or are extremely expensive. Manufacturers are also finding increased requirements for connectivity, networking, and user interface functionality.

It is difficult for manufacturers to justify the high cost of replacement of their production systems based on these factors alone. Cost of replacement involves many components. While the robotic manipulator is a high cost component in a system, other costs closely associated with the manipulator are the end-of-arm tooling and the part fixturing equipment. Add to these the cost of fencing, safety gating, utility hook ups, break down and installation costs for new equipment, training costs, documentation costs, spare parts inventory costs, project management costs, and quality assurance verification costs. Considering all these factors, the price of replacing an existing system can be, many times, the cost of the equipment.

In many cases such as in the case of the ECIS, the only outdated equipment in the system is the control computer itself. ARC's customers have found that, for a tiny fraction of the total cost of a completely new production system, manufacturers can leverage their existing capital equipment investment and have the latest technology in factory floor production equipment.

## 1.3 Benefits

The ARMotion robot controller upgrade on the ECIS machines offer the Air Force the following benefits:

- Higher performance motion control for smoother motion and better signal-to-noise ratio during measurements

- Latest technology hardware eliminates obsolete components

- Windows NT V4.0 operating system, familiar to personnel, easy to use, shorter learning curve

- Windows style Graphical User Interface, familiar text boxes, pulldown menus, click boxes, etc.

- High brightness active matrix touch screen for intuitive, easy to use operator interface

- Visual Basic V5.0 application software for easy programming and updating

- Readily available, low cost components available from any PC component supplier

- Extensive built-in robotic control functionality for future Scan Plan enhancements

- COTS product that is continually being updated by the vendor without cost to the Air Force

- Runs all ECIS versions, allows complex geometries like F220 to be run on Version 1 or Version 2 machines

- High speed serial port communications will speed up operation when station computer upgrade is complete

- Easy motor drive tuning

- Built-in diagnostic screens for ease of troubleshooting

## 2.0 Technical Overview

The robot controller upgrade is based on American Robot Corporation's ARMotion robotic control system, a multiple machine robot controller capable of 24 axes of kinematically coordinated motion. This is a commercial off-the-shelf product of ARC which has been designed to be a universal robot controller capable of controlling a wide variety of robotic manipulator configurations. The goal of this project was to adapt this standard product to meet the requirements of the ECIS machine.

### 2.1 The ARMotion Robot Controller

The ARMotion robot controller (Figure 1) is a PC based, dual processor industrial computer capable of real time, simultaneous, coordinated control of up to 4 separate kinematic manipulators, or robots. Each manipulator may have up to 6 axes, for a total capability of 24 axes of motion. It uses standard industrial PC components to minimize proprietary content, avoid obsolescence, and provide the customer with the ability to source low cost replacement parts. The customer can add additional components to expand the system or to provide additional functionality. Third party technology, anywhere from keyboards/monitors to speech recognition/vision systems, can be integrated easily by the user.
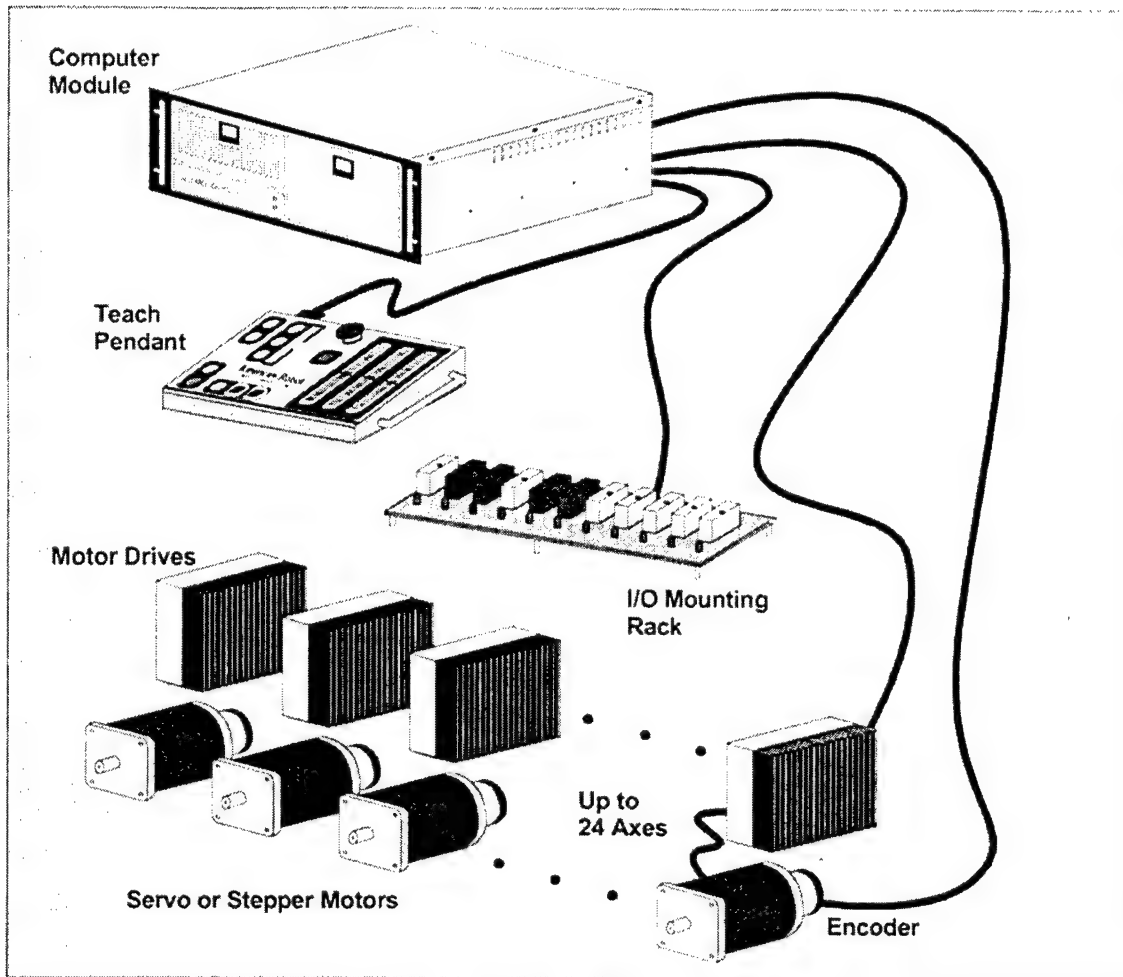
5

Figure 1 - The ARMotion Controller

While several different package configurations are available, the ECIS uses the 19" rack style packaging and passive backplane construction. The ARMotion system handles the real time requirements of robotic control by using two separate Single Board Computers (SBC's) in the system. These are both located on the same backplane, but the backplane is segmented. This essentially creates two separate PCs in the same case.

The **master PC** runs Windows NT Workstation. The **servo PC** controls the motors in an isolated environment, not subject to the unreliable and non-deterministic properties of an operating system based computer. It is essentially an embedded controller that utilizes PC hardware.

The basic configuration of the ARMotion controller is that of an ordinary PC with the following exceptions:

    - The system chassis contains two separate PCs.

6

- The servo PC, has no disk drives and runs no operating system. Its job is to keep constant track of the servomotors and to monitor safety conditions. It is connected to the master PC through a local area network. The servo PC's operating software is installed across an internal network by the master PC.

- There are 2 types of ARC proprietary ISA buss I/O cards installed in the chassis. These interface to the encoders and the motors.

The servo PC continually monitors the encoders and calculates the servo algorithms that position the motors. The master PC runs Windows NT and the user's application. The servo PC executes the servo code in a protected, isolated environment.

This separation of duties prevents critical errors such as crashes or runaways which could be caused by hang-ups on the user interface or Windows NT end. If the master PC were to hang up in any way, the motors will not be effected. The servo computer also contains a watchdog timer. This circuit continually monitors the servo software for proper operation, and if it detects a fault, shuts down motor power.

## 2.2 The ARMotion Configuration for the ECIS System

Many options and configurations are available for the ARMotion controller. For the ECIS system, a special configuration was developed. The hardware configuration is illustrated by the backpanel view in Figure 2.
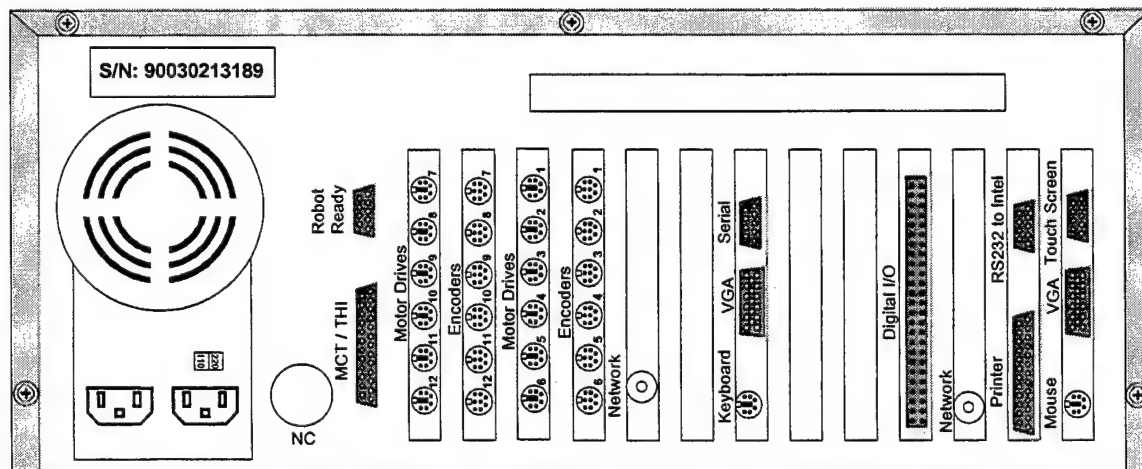


**Figure 2 - ARMotion Backpanel Configuration for the ECIS**

The slot configuration is as follows (Table 1); slot 1 is the rightmost slot viewed from the back of the controller.

**Table 1 – Slot Configuration**

| Location | Description | Part Information |
|---|---|---|
| Hard Disk | COTS EIDE style 6.4 GByte hard disk | Western Digital Caviar |
| Floppy Disk | COTS 1.44 Mbyte floppy drive | Teac |
| Power Supply | Generic 250W power supply | |
| Chassis | 14 slot rack mount chassis with passive backplane | |
| Slot 1 | Main PC single board computer. 200 Mhz MMX Pentium. Refer to individual manual for complete information | Axiom Tek SBC8251 |
| Slot 2 | connector bracket | supplied with SBC8251 |
| Slot 3 | Generic ARCNET network board | |
| Slot 4 | Sound Card | OPTI831 |
| Slot 5 | I/O board | NuDac-7122 144 bit I/O |
| Slot 6 | | |
| Slot 7 | | |
| Slot 8 | Servo PC single board computer. 166 Mhz Pentium. Refer to individual manual for complete information | Axiom Tek SBC8251 |
| Slot 9 | | |
| Slot 10 | Generic ARCNET network board with ARC supplied boot EPROM | |
| Slot 11 | ARC proprietary PCEMIC Encoder Board for the first six axes | ARC P/N: 105000 |
| Slot 12 | RC proprietary PCAMIC Motor Drive Interface Board for the first six axes | ARC P/N: 105004 |
| Slot 13 | ARC proprietary PCEMIC Encoder Board for axes 7-12 | ARC P/N: 105000 |
| Slot 14 | ARC proprietary PCAMIC Motor Drive Interface Board for the axes 7-12 | ARC P/N: 105004 |

## 2.1 ECIS Manipulator

The ECIS manipulator has seven axes of servo controlled motion. Each axis is driven by a DC servo motor and PWM amplifier with optical encoder feedback. The machine includes a six-axis cantilever gantry robot with the seventh axis being the turntable.

The six-axis gantry robot has the normal X, Y, and Z axes common to standard gantry robots, but the wrist configuration is unique. The wrist is a pitch – plunge – roll configuration, with the pitch axis fixed in the X - Z plane. The pitch axis is known as the 'B' axis. Directly affixed to the B axis is a plunge, or linear, axis known as the 'ZZ' axis. Rotating about the ZZ axis is the 'S' or spindle axis.

The gantry robot and turntable are mounted on a granite slab along with a manual control station, a probe carousel, and various ancillary equipment as shown in Figure 3.
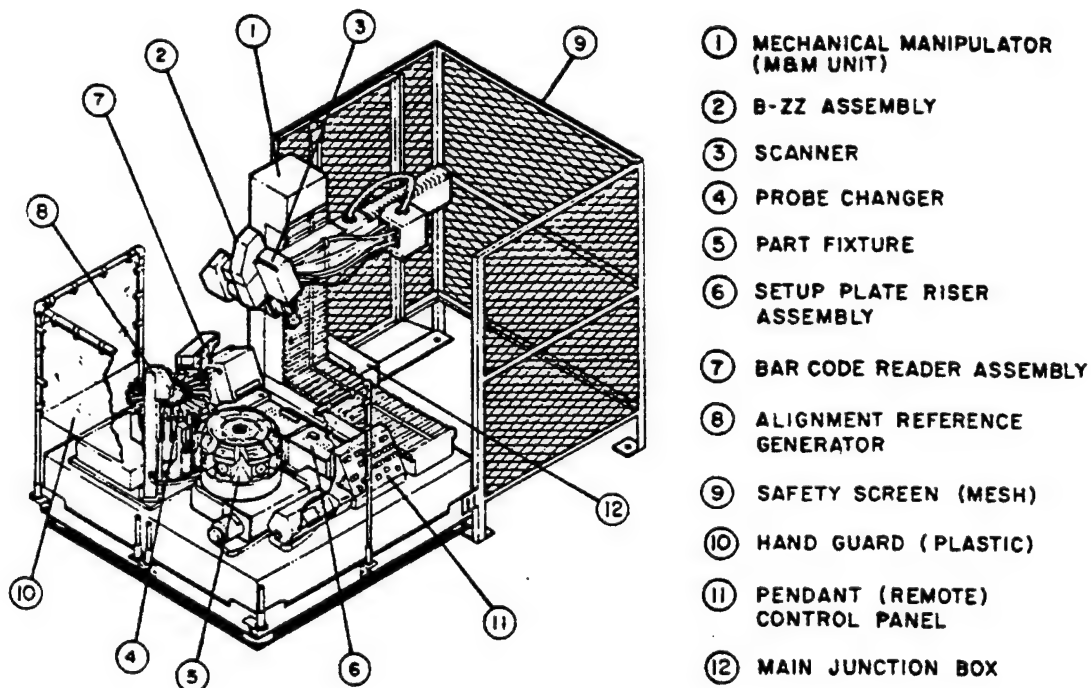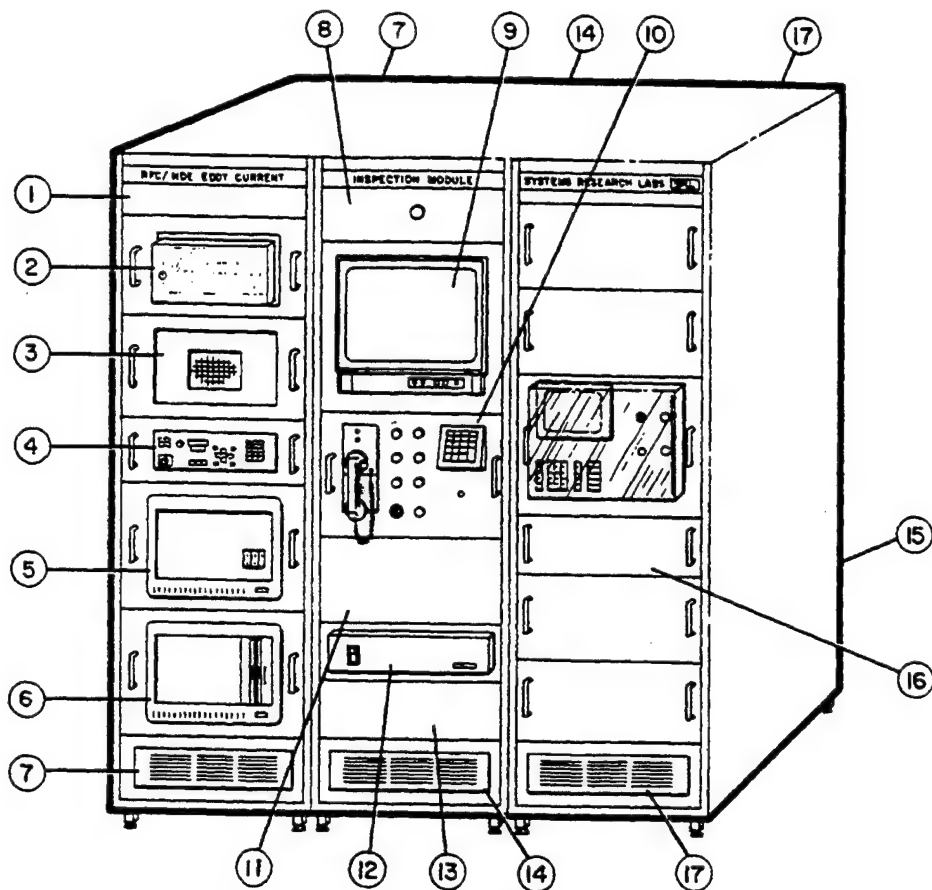


1. MECHANICAL MANIPULATOR (M&M UNIT)
2. B-ZZ ASSEMBLY
3. SCANNER
4. PROBE CHANGER
5. PART FIXTURE
6. SETUP PLATE RISER ASSEMBLY
7. BAR CODE READER ASSEMBLY
8. ALIGNMENT REFERENCE GENERATOR
9. SAFETY SCREEN (MESH)
10. HAND GUARD (PLASTIC)
11. PENDANT (REMOTE) CONTROL PANEL
12. MAIN JUNCTION BOX

**Figure 3 - The ECIS Manipulator**

There are three different versions of the ECIS now in operation. These are known as Version 1, Version 2, and Version 3. There are four Version 1 machines in existence, all at Kelly Air Force Base. One of these has now been

upgraded with the new robot controller. There is only one Version 2 machine, it is at Tinker AFB. It has also been upgraded with the new robot controller. All the remaining machines are Version 3 machines. Two of these Version 3 machines have been upgraded. All these systems are similar, but some differences exist in the work envelope, computer revision levels, scanner design, motor drives, wiring, and feedback ratios. In addition, there are presently two obsolete versions of the robot controller. Version 1 and Version 2 machines used the original Allen Bradley 8400 robot controller. Version 3 machines use the M&M Precision robot controller.

## 2.2 The ECIS Controller

The ECIS controller has three 24" rack mount style bays. Viewed from the front, the right most bay contains the robot controller, the motor drives, and the I/O control racks. All modifications to the robot controller were performed in this bay. The original configuration is shown in detail in Figure 4.

**Figure 4 - The ECIS Control System**

**LEFT CABINET ASSEMBLY**

① BLANK PANEL

② TEKTRONICS OSCILLOSCOPE WITH COVER

③ NDT-25L INSTRUMENT DISPLAY ASSEMBLY

④ NDT-25L NDT INSTRUMENT CONTROL ASSEMBLY

⑤ INTEL 86/380 CPU

⑥ INTEL 86/380 DISK DRIVE CHASSIS ASSEMBLY

⑦ BLOWER ASSEMBLY, LOWER FRONT AND UPPER REAR

**CENTER CABINET ASSEMBLY**

⑧ VISUAL ALARM PANEL ASSEMBLY

⑨ AED-767 COLOR DISPLAY

⑩ OPERATOR CONTROL ASSEMBLY

⑪ OPERATOR KEYBOARD ASSEMBLY

⑫ AED-767 CRT CONTROLLER ASSEMBLY

⑬ AC POWER DISTRIBUTION ASSEMBLY

⑭ BLOWER ASSEMBLY, LOWER FRONT AND UPPER REAR

⑮ REAR CONNECTOR PANEL ASSEMBLY

**RIGHT CABINET ASSEMBLY**

⑯ MECHANICAL MANIPULATOR ELECTRONIC COMPONENTS

⑰ BLOWER ASSEMBLY, LOWER FRONT AND UPPER REAR

The new configuration with the upgraded robot controller is shown in Figure 5.
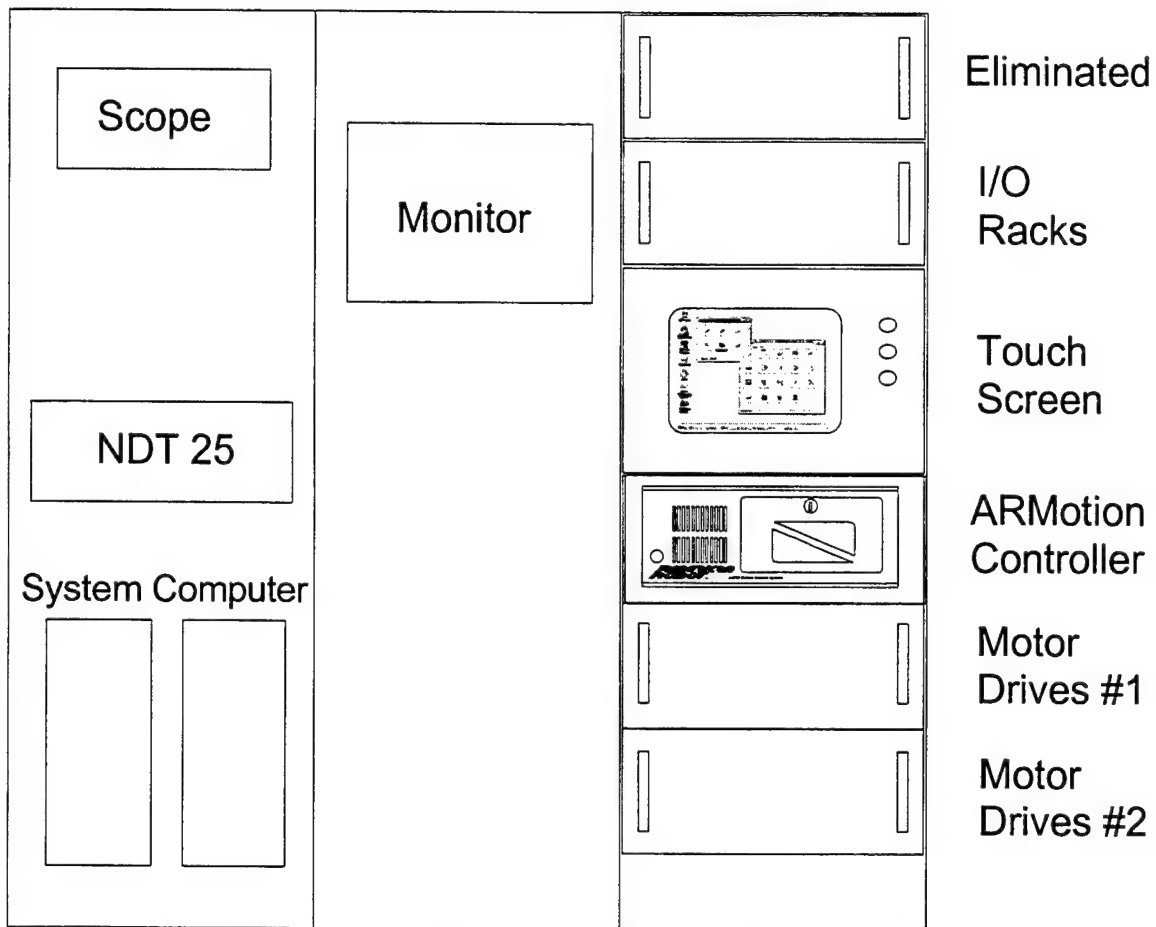
**Figure 5 - The Upgraded ECIS Controller**

## 2.3 Special Requirements

One special feature was required by the ECIS system that was not standard on the ARMotion system. This was the ability to capture the actual position data within 5 microseconds of a pulse on an I/O signal from the station computer. This signal is called Threshold Interrupt, or THI.

The ECIS system computer issues a THI when the eddy current signal breaks a preset threshold, indicating a flaw has been detected. The robot controller is required to accurately capture the position of the manipulator so that the location of the flaw can be recorded.

Circuitry and software was designed and incorporated into the ARMotion controller to provide this function. This capability is now included as a standard feature in all ARMotion controllers.

12

## 2.4 The Application Software

The largest part of the development effort was the development of the application software. This program, RFC.EXE, is the main user interface to the motion control system, and is responsible for translating the commands coming across the serial port from the host computer into a format compatible with the ARMotion system software.

The ARMotion robot controller is an "open architecture" design. Open architecture systems provide their intended level of functionality without limiting the user in other areas. For instance, a non-open system would be a robot controller which provided a proprietary robotic programming language, developed by the robot supplier. The language capabilities would be limited to the functionality included in the programming language. For example, an interface to one type of vision system might be included, but another might not. Or perhaps there may be no bitmap support, etc.

To eliminate these types of restrictions, the ARMotion system software is supplied as a WIN32 compatible Dynamic Link Library, or DLL. The robot control functions are available through DLL calls from an EXE program. This way, the user is "open" to use any programming system that is required for the application, and can make use of third party technology which is supplied in a similar "open" format.

For the ECIS, a program (RFC.EXE) was developed in Visual Basic V5.0. This program calls the ARMotion DLL for robotic control functions. Example functions available in the DLL are:

- move_cmd( param1,param2, etc. , ,)      which moves the robot
- capture_cmd( param1,param2, etc. , ,)      position capture
- circle_cmd( param1,param2, etc. , ,)      sets up a circular path
- vel_on_cmd( param1,param2, etc. , ,)      commands a joint velocity

Many such functions are available for a wide range of robotic control tasks.

RFC.EXE has several main components:

- A command processor. This section interprets the ASCII command strings, or "patterns" into motion and I/O commands to the ARMotion system. These patterns contain G code style commands which were native to the Allen Bradley 8400 robot controller in the original ECIS machines.

- A communication interface with the station computer. This section supports the proprietary protocol that was used to transport messages

13

across the RS-232 link between the station computer and the original AB8400 robot controller.

- A Graphical User Interface. As with any Windows NT application, many windows, frames, textboxes, clickboxes, have been provided for the operator to control the functions of the machine.

Most importantly, the RFC.EXE application source code is in control of Air Force personnel. It is easy to read, well documented, and can be compiled on any desktop PC with Visual Basic V5.0. This gives the Air Force the capability to troubleshoot, expand, and upgrade the operational software without having to rely on an outside vendor.

## 2.5 Structural Dynamic Analysis

The ARMotion controller has a very powerful servo system for precision motion control. Many of the algorithms employed in the servo system software perform optimally when an accurate definition of the mechanical system is determined in advance. To characterize the mechanical system dynamics, FFT analysis was performed on ECIS #5 in Dayton, a Version 1 machine.

An FFT analyzer was used to inject pink noise into the velocity command input on the servo drive for each axis, and the resultant velocity was measured on the tachometer. A transfer function calculation was performed to determine the phase and magnitude relationship between the input excitation and the output response. The tachometer remained connected to the servo drive to provide negative velocity feedback and stabilize the loop. This configuration is known as a 'closed velocity' loop.

In this configuration, FFT analysis can determine if there are any structural resonances in the band of frequencies of interest, or if there is any peaking in the closed loop portion of the loop which would cause oscillation during motion. Also, optimized compensation can be calculated for the position control loop given the actual parameters of the velocity control loop.

For each axis, two tests were performed, one with a high frequency content out to 5 Khz, and one with a low frequency content out to 150 Hz. The results of each test are summarized in two plots, a phase plot and a magnitude plot of the closed loop transfer function. The high frequency test was performed to get an overall view of the wideband performance of the loop and to look for any high frequency problems such as torsional resonances between the motor/tach and the load. The high frequency test is not very accurate in the low end. The low frequency test is the main focus for the analysis of the loop performance.

14

A sample of the data that was collected is given below for the X axis. While the DC component of the magnitude in the following Bode plot shows 10 db, this is due to a DC gain in the test setup. Actual DC gain is 0 db.
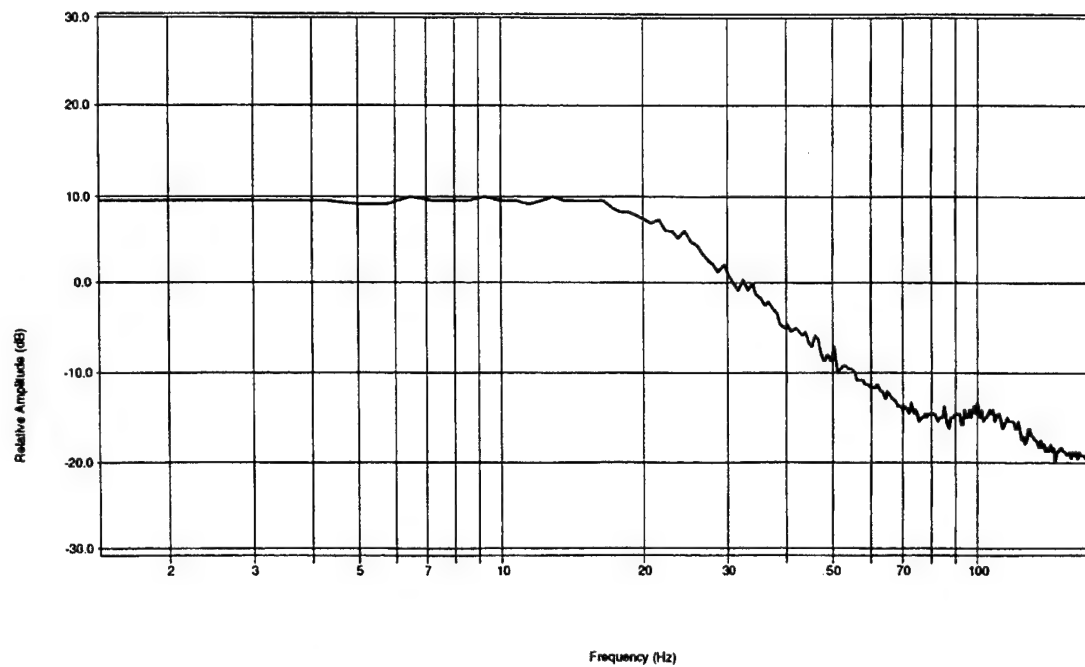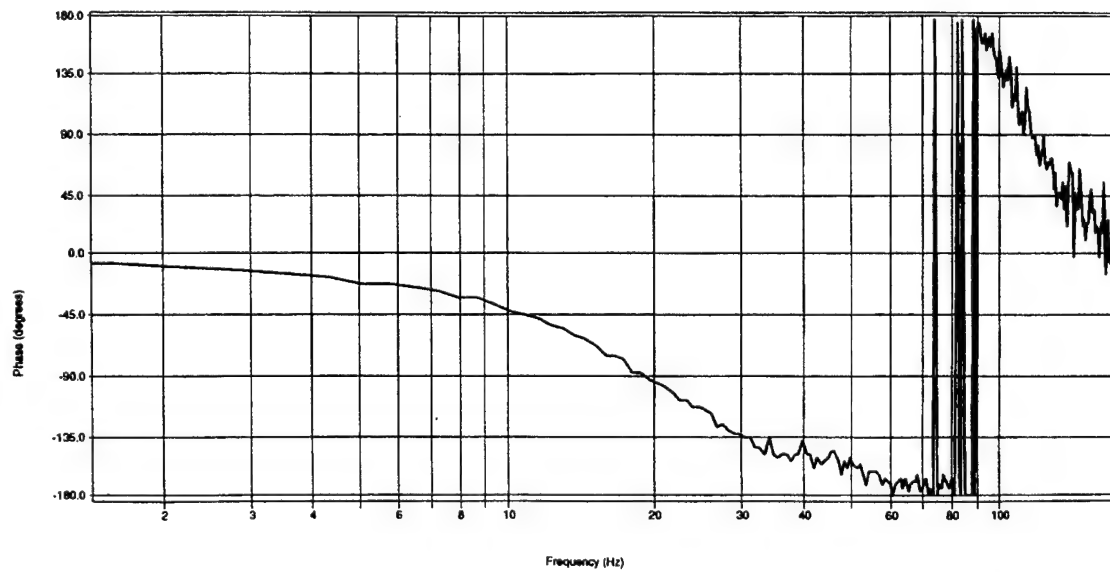


**Figure 6 - X Axis Magnitude Response**



**Figure 7 - X Axis Phase Response**

15

The overall testing is summarized in Table 2. These figures were used to set up the servo system parameters in the ARMotion software.

**Table 2 – Axes Structural Responses**

| Axis | Resonance | Bandwidth | Damping | Comments |
|------|-----------|-----------|---------|----------|
| X | 80 Hz, low amplitude, good damping | 19 Hz | somewhat underdamped | Resonance is no problem due to its small amplitude. Probably a torsional mode of entire X axis around Z column. |
| Y | 80 Hz, very low amplitude. Torsional tach resonance at 2.8 KHz, 20 db margin | 40 Hz | somewhat underdamped | 80 Hz resonance is probably a reflection of X torsional mode around Z. Should reduce servo gain to be more compatible with other axes. |
| Z | 2.3 KHz tach torsional, 20 db margin | 18 HZ | somewhat underdamped | |
| B | 2.3 KHz tach torsional, 12 db margin | 40 Hz | somewhat underdamped | Should reduce servo gain to be more compatible with other axes and provide more margin on tachometer mode which is a little high. |
| ZZ | 2.3 KHz, 22 db margin | 45 Hz | critically damped | |
| CC | 100 Hz low amplitude, good damping | 20 Hz | critically damped | Only tested with no load. Should characterize change with micro manipulator. |
| C | 30 Hz, high amplitude, 6 db margin | 20 Hz | badly underdamped | Low frequency, high amplitude peak probably due to low turntable stiffness. Varies with table loading, close to pass band. Will cause noticeable oscillation on motion. |

The conclusions of this testing were that the machine exhibits excellent structural properties, great stiffness, good damping, and is generally well designed. The only exception is the C or turntable axis, which was only tested on a Version 1 machine. This same turntable is used on the Version 2 machines, but the majority of machines in use are Version 3 machines which have a redesigned turntable.

# 3.0 Implementation

There are three versions of the ECIS system as previously described. In addition, there are subtle wiring differences between each machine. This made the installation process more difficult than expected.

Originally, the project called for a 'drop in' replacement robot controller that would be compatible with the existing connectors on the older robot controller. To this end, a set of adapter cables was designed and implemented on the first ECIS upgraded. These adapter cables proved to be bulky and impractical. A new design eliminated these adapter cables by providing cable assemblies which simplified wiring and improved reliability. Now, the robot controller is still a 'drop in' replacement, but the robot controller and cable assemblies are considered all part of the same assembly. In order to convert from the old robot controller, the old controller complete with the old cable assemblies must be removed, and the new robot controller with its cable assemblies must be installed.

The original adapter cables installed in the first machine that was upgraded have been removed, and none of these original cables are now in existence. All four upgraded machines now use the same cabling scheme.

## 3.1 Installation Kit

Each controller is supplied with an installation kit which was designed to interface the robot controller to the hardware of the ECIS system. This consists of:

- (7) encoder interface cable assemblies
- (7) motor drive interface cable assemblies
- (1) interface cable assembly
- (2) motor power interface relays
- (1) MCT/THI connector kit

The installation kit is identical for each version of the ECIS, however wiring differences between the versions and from machine to machine in the same version level make the exact connections vary in each installation.

## 3.2 Installation

Controller installation on an operational ECIS machine takes about 1 man day. It requires an additional day to clean up the wiring, tune the motor drives and debug the machine. One to two additional days are recommended for qualification of the machine.

During installations on this project, it became apparent that there were operational differences as well as wiring differences from machine to machine. This complicated the installation process. Some of the machines have difficulties running some of the inspections. For all future installations, it is recommended that the acceptance criteria be established prior to the installation and run on the existing configuration. For example, if it is decided that the acceptance test should include an F110 4-9 spool and F110 $2^{nd}$ stage fan, these should both be run on the machine before any modifications are made. Upon completion of the installation, these tests can be re-run and the results compared with the pre-upgrade results.

### 3.3 Motor Drive Upgrade

The motor drives presently in use on all versions of the ECIS are outdated, and difficult and expensive to repair. In particular, the Version 1 and Version 2 machines use motor drives of an even earlier series, and the drive transistors are no longer available for repair. When drives are repaired, the vendor installs new 'power block' style transistors which add approximately 2" to the outside dimension of the drive which makes it impossible to physically fit the motor drive into its original mounting space.

During the course of installation of the ARMotion controller on the Version 2 machine at OC-ALC, some problems were detected in the motor drive for the turntable axis. As ARC was familiar with the latest offerings on the market for motor drives, ARC was able to easily specify a new style low cost, high performance motor drive which was subsequently installed and tested in this axis. These drives utilize a 33 KHz switching frequency, and eliminate the need for the bulky choke inductors required for the original 5 KHz switching drives. The size of the new style drive is about that of a cigarette pack, vs. the 'loaf of bread' size of the older drives. The new drive's performance exceeded that of the original drive, and its purchase cost is about one third of the repair cost of the older drives. Plans have been made to eventually replace all motor drives with this new style. This was an unexpected side benefit of the project.

# 4.0 Testing and Performance Evaluation

A large portion of the development effort was spent in the field at SA-ALC debugging the RFC.EXE application software. This effort was much larger than expected due to the lack of documentation on operation of the existing robot controller. Documentation on the operation, timing, and sequencing on many of the commands was non-existent, and had to be reverse engineered in the field. No source code or internal software documentation was available for the previous versions of the robot controllers.

Additional problems were found during the debugging phase that were due to problems in Scan Plan supervisory programs. A Scan Plan is the program that runs on the station computer which coordinates the inspection between the user interface, eddy current instrument, and robot controller, and collects and analyzes the data received from the probe. Some of the scan plans have errors that were never discovered due to the idiosyncrasies of the operation of the robot controller. Modifications were made to the new controller to accommodate these errors where possible.

One of the goals of the project was to provide documented source code to the Air Force to avoid these types of problems in the future. The RFC.EXE application program provides the internal documentation on the detailed operation of the robot controller, allowing the Air Force to easily debug operational problems in the future. It has also been designed to allow for easy expansion. Adding G Codes, M Codes, changing operational sequences, or adding user interface screens are now easy changes AF personnel can do without having to contact the robot control vendor for a special software revision.

## 4.1 Functional Testing

Functional testing was performed on the F100, F110, and F220 engines. This consisted of running parts that utilize as many of the different inspection commands in the scan plans as possible. Inspections tested included surface, RECCHI, wide field broach slot, scallops, and micro manipulator broach slots. The following parts were tested:

F100 1st stage Fan
F100 9th stage HPC
F100 12th stage HPC
F220 1st stage Fan
F220 4th stage HPC
F220 9th stage HPC
F220 12th stage HPC
F220 1st stage HPT

F220 11th stage Air Seal
F110 4-9 spool
F110 1st stage LPT
F110 2nd stage Fan
F110 3rd stage HPC
F110 Forward Outer Air Seal
F110 HPT Disk
F110 Front Shaft
F110 Aft Shaft
F110 HPC 1-2 spool

All of these parts were run successfully with the following exceptions:
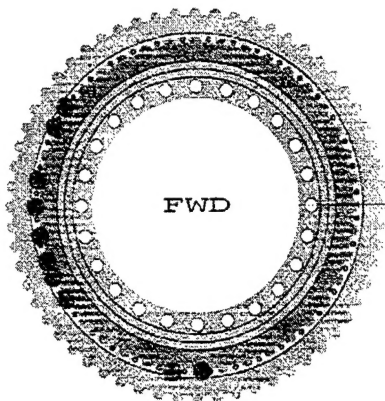
- The dovetail slot inspections using the 106 probe failed on slot centering on ECIS #15 at OC-ALC

- F110 aft shaft RECCHI probe failed on centering on ECIS #1 and ECIS #15 at OC-ALC

- Rabbet_39 test failed on ECIS #15 at OC-ALC

All these problems are thought to be scan plan or machine problems, none are thought to be due to the robot controller.

### 4.2 Performance

Performance testing was conducted on a notched part, the F220 4$^{th}$ stage compressor disk at SA-ALC. The objective of this testing was to determine what effect, if any, the robot controller had on the reliability of flaw detection. The F220 4$^{th}$ stage compressor disk was chosen because it uses continuous path motion with special G Code commands (contoured motion) to smoothly move the 802 probe across the scallop section of the disk. Any vibration in the movement of the machine is critical during this inspection, and could cause false indications.

The tests were done three times. Each time, every flaw which exceeded the reject criteria was detected reliably, consistently, and in the same place. One of the three test results is shown in Figure 8.

Figure 8 - F220 4th HPC Notched Part Scallop Testing

These three tests were compared to historical data on the same part using the old M&M robot controller. Four test results were available using the M&M, on two different ECIS stations (#17 and #18), using two different probes ('B' probe and 'Y' probe).

Tables 3 and 4 summarize the results of the seven tests.

### Table 3 - ARC Controller Tests

| Flaw | Cycle 2 Depth | Cycle 2 Depth | Cycle 3 Depth | Delta Depth |
|------|---------------|---------------|---------------|-------------|
| 1 | .0097" | .0088" | .0086" | .0011" |
| 2 | .0104" | .0102" | .0096" | .0008" |
| 3 | .0111" | .0106" | .0116" | .0010" |
| 4 | .0117" | .0112" | .0112" | .0005" |
| 5 | .0105" | .0100" | .0101" | .0005" |
| 6 | .0128" | .0121" | .0132" | .0011" |
| 7 | .0105" | .0100" | .0097" | .0008" |
| 8 | .0124" | .0116" | .0124" | .0008" |
| 9 | .0112" | .0102" | .0104" | .0010" |
| 10 | .0124" | .0117" | .0118" | .0007" |

### Table 4 - M&M Controller Tests

| Flaw | ECIS-17Y | ECIS-17B | ECIS-18Y | ECIS-18B | Delta Depth |
|------|----------|----------|----------|----------|-------------|
| 1 | not detected | not detected | not detected | not detected | ---- |
| 2 | .0091" | not detected | not detected | not detected | ---- |
| 3 | .0110" | .0109" | .0089" | .0091" | .0021" |
| 4 | .0109" | .0104" | 0.0090" | .0088" | .0021" |
| 5 | .0098" | .0093" | not detected | not detected | ---- |
| 6 | .0128" | .0126" | .0105" | .0107" | .0023" |
| 7 | .0092" | .0084" | not detected | not detected | ---- |
| 8 | .0122" | .0118" | .0095" | .0098" | .0027" |
| 9 | .0095" | .0089" | not detected | not detected | ---- |
| 10 | .0118" | .0110" | .0100" | .0093" | .0025" |

While the three tests run with the ARC data were run on the same machine with the same probe so the results cannot be exactly compared to the M&M tests, the following can be observed:

- the ARC controlled machine found all flaws consistently

- the M&M controlled machines failed to find many of the flaws

- the difference in the depth of the cracks detected by the ARC machine were 2 to 4 times more consistent than the depths reported by the M&M controlled machines when they did find the flaws

This consistency is most likely due to the quality of the motion control of the ARC controller. Continuous path motion is very smooth, and ARC's velocity blending algorithms use third order spline interpolators to minimize "jerk," or the derivative of acceleration, during motion transitions. This was also noticed during the testing using the debug window in the graphics screen where the sampled data can be observed. SA-ALC personnel observed that the signal-to-noise ratio appeared to be much better than that with the M&M controller where "bumps" could be seen in the signal during data collection.

## 5.0 Results, Conclusions, and Future Recommendations

Four systems have been installed to date and are operational.

With a relatively small up-front expenditure, the Air Force has developed, tested, and implemented an on-line-replacement upgrade for its RFC capability. It has replaced an expensive, custom designed, obsolete, green screen/numeric keypad controller with a commercial off the shelf, Windows NT, active matrix touch screen PC with better motion control performance at approximately half the cost.

It is recommended that further work be done on the motor drive upgrade discussed in Section 3.3. Replacing the drives with up-to-date units will not only result in a cost savings, but will increase performance and reduce system downtime.